

Measurement and Analysis of Vibration Levels on Warehouse and Retail Store Material Handling Equipment

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ABSTRACT: Material Handling Equipment (MHE) is widely used to move packaged goods from manufacturing to warehousing, storage, transportation, in both warehouses and distribution centers to retail stores. Moving product between facilities is done by different types of equipment ranging from manually pushed carts to automated vehicles. A considerable amount of research has been conducted to evaluate the ergonomics of manual or mechanized MHE in the past. There is, however, no published work documenting vibration conditions that occur when transporting packages using MHE. This study measured the vibration levels for typical MHE used at warehousing facilities. Power spectral density plots were generated for both loaded and empty configurations of the seven types of MHE. Vibration levels for both the inside and outside floor and pavement surface conditions at warehouses were also studied.

1.0 INTRODUCTION

IN recent decades, there has been a steady increase in the development of free trade agreements in all regions of the world. Products once produced for domestic markets must now be able to compete in international markets without trade barriers. The complexity of managing global supply chains demands equipment and systems that is responsive, flexible, and aligned. According to the Material Handling Industry of America, *material handling and logistics is the movement, protection, storage and control of materials and products throughout the process of their manufacture and distribution, consumption and disposal* [1]. One

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of the largest and fastest growing industries, the consumption of material handling and logistics equipment in the US, exceeds \$125 billion annually [1].

The MHE industry, with leaders such as NACCO Industries in the US, Linde AG in Europe and Toyota in Asia, is considered to be highly fragmented, with the 50 largest companies accounting for 35 percent of the market [2]. In the US alone approximately 4000 distribution outlets for MHE generate combined annual sales of \$15 billion, about half due to fork lift truck sales [2]. The US market for MHE and systems is estimated to reach \$20.4 billion in 2008 [3]. This demand is expected from technological innovations such as material handling robots, automated guided vehicles and high end services.

Material handling equipment (MHE) is primarily used for the movement and storage of goods within a facility or at a single site. MHE can be broadly categorized into the following [4]:

1. *Transport equipment*: includes equipment, such as carts, pallet jacks and trucks, conveyors, cranes and industrial trucks, used to move material between locations. The locations could be between workplaces, between a loading dock and a storage area, etc.
2. *Positioning equipment*: includes equipment, such as hoists, industrial robots and dock levelers, used to handle material so that it is at the desired location and position for subsequent handling, machining, transport, or storage.
3. *Unit load formation equipment*: includes equipment, such as pallets, totes, intermodal containers and stretch wrappers, used to control materials so that they maintain their integrity when handled as a unitized load during distribution.
4. *Storage equipment*: includes equipment, such as racks, carousels and mezzanines, used for holding materials over a period of time for an optimum throughput.
5. *Identification and control equipment*: includes equipment, such as bar codes, RFID and machine vision, used to collect and communicate information needed to coordinate proper flow of materials within or between facilities as well as between suppliers and customers.

Material Handling Equipment (MHE) is widely used to move packaged goods through the supply chain, from manufacturing to warehousing, to storage, and for transportation, in both warehouses and distribu-

tion centers. Product moving within a facility is carried by different equipment ranging from manually driven carts to automated vehicles. A considerable amount of research has been conducted to evaluate the ergonomics of manual or mechanized MHE in the past.

A superstore stocker spends nearly 74% of his shift duration in manual material handling [5]. During a shift a stocker's activities involve nearly 200 handling operations which include handling of fragile and unstable merchandise [5]. Material handling in a grocery store or warehouse is commonly carried out using various types of carts, pallet jacks and fork-lift trucks. Such MHE encounters various surfaces during transportation both inside and outside a facility. The force required to push carts over surfaces depends on its coefficient of friction (COF) [6]. It has been established that the maximum acceptable weight to push a cart on a low COF surface is 31% lower than high COF surface. Also, the initial and sustained force required to push the cart has been found to be significantly lower for low COF surfaces than high COF surfaces [6]. However, the vibration levels associated with hand pushed cart either on a low or high COF floors has not yet been studied.

The importance of measuring and quantifying the vibration levels occurring during transportation (inside tractor trailers) as it relates to damage has been established in previous study [7]. It is also known that the vibration forces experienced by a truck traveling on various road surfaces generate different vibration levels leading to product damage [8]. Similarly a manually operated cart can generate different vibration levels as a result of different wheel design (casters), floor surface and load on cart. Resnick and Chaffin [9] studied the optimum handle height and maximum load on carts to reduce biomechanical stress among operators. They recommended that the maximum load on a four wheel cart should be 225 kg from a biomechanical stand point. Regardless of this recommendation it has been observed that load weight on a four wheel cart can be as high as 1500 kg [10]. Therefore, it may be hypothesized that the vibration levels may vary on a four wheel cart depending on the weight transported. Previous studies conducted have had a major focus on measuring and analyzing transportation vibration levels. There is, however, no published work documenting vibration conditions for MHE.

The focus of this study was to compare the difference in vibration levels for commonly used MHE in warehousing operations and develop methods to simulate these conditions in a laboratory environment using

tests methods such as American Society of Testing and Materials (ASTM) D4728 [11]. The results of the vibration data analysis are presented as Power Density Spectra. A Power Density Spectrum is a plot of energy (Power Density) versus frequency [12] and this is commonly used to measure and compare vibration levels].

The levels of acceleration occur in a random manner over a range of frequencies when vibration data is collected in truck shipments. The average power density within a band of frequencies is calculated as follows:

$$PD = \frac{1}{BW} \sum_{i=1}^n (RMS G_i^2) / N$$

where, $RMS G_i$ is a sampled root mean square acceleration value measured in g's within a bandwidth (BW) of frequencies, and N is the number of instants sampled. The corresponding PD levels are then plotted against the center frequency of the bandwidth to develop the power density spectrum for the data set analyzed. For this study a bandwidth of 1 Hz was used.

A PSD plot is an important tool used in simulating real life transportation environments using vibration equipment in a laboratory. Figure 1 below shows an example of an actual PSD plot for loaded trailer with leaf spring suspension going over interstate expressway used to simulate a truck ride on a vibration table. Some of the typical sources of vibration are also defined [13].

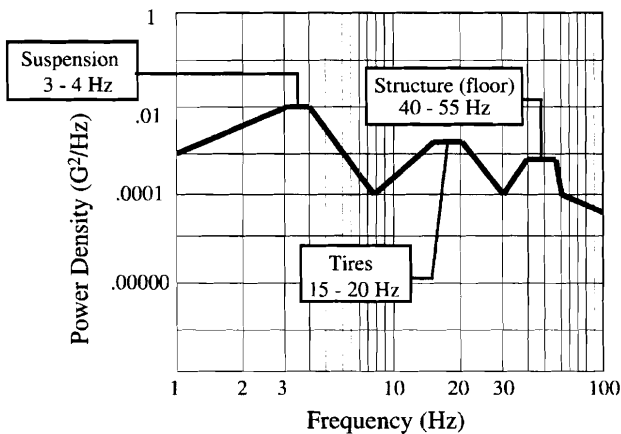


Figure 1. A Typical PSD Plot for Truck Transportation.

Due to a lack of data from past studies, this research focused on measuring and analyzing the vibration levels for MHE for various floor surfaces. Specifically it had the following objectives:

1. Measure vibration levels in all three axes of the MHE (latitudinal, longitudinal and vertical).
2. Determine the range of vibration levels between empty and fully loaded (by weight capacity of MHE) MHE on a range of surface conditions.
3. Measurements of vertical vibrations on empty MHE both on the inside and outside surface conditions representative of warehouse and retail store conditions.
4. Recommend a vibration test to simulate these conditions.

2.0 MATERIALS AND INSTRUMENTATION

A field data recorder SAVER™ 3X90 by Lansmont Inc. (Monterey, CA) was used to capture vibration levels for all MHE studied. This self-powered instrument provides 16 bit resolution, internal tri-axial accelerometer, temperature and humidity sensors, USB connectivity, and is operable in the field for up to 90 days [13]. The SAVER™ 3X90 provides information about motion, vibration, temperature and humidity. An internal clock marks the exact time when each event occurs. The SAVER™ 3X90 units were mounted on carts and fork lifts using magnetic mounts or clamps. Figure 2 shows a SAVER recorder mounted on a cart for vibration measurement.

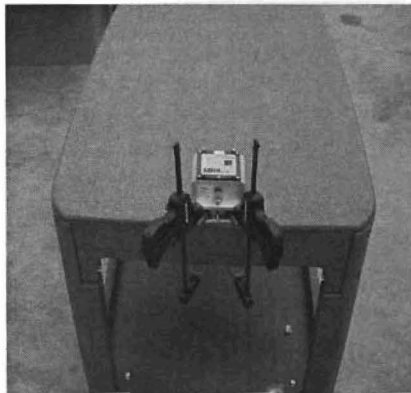


Figure 2. Mounting of Recorder on Push Carts.



Figure 3. Grey Plastic Cart.

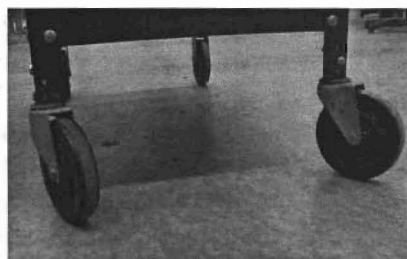


Figure 4. Grey Metal Cart.

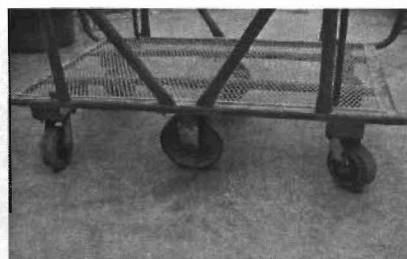


Figure 5. Red Metal Cart.



Figure 6. *Green Metal Cart.*

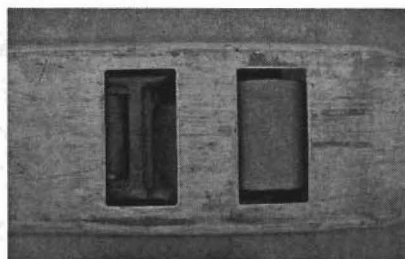


Figure 7. *Pallet Jack.*



Figure 8. *Fork Lift Truck.*



Figure 9. *Stacker.*

Table 1. *Material Handling Equipment Tested.*

	Length (in)	Width(in)	Height (in)	Capacity (lb)
Plastic Grey	40-1/2	25-1/2	33-3/4	400
Metal	36	24	32	400
Pallet Jack	53	26-1/2	47 (Ground to Handle)	5500
Green Wooden	72	36	30 (Ground to Handle)	1200
Red Metal	60	30	30	2000

This study measured the vibration levels experienced by four commonly used manual push carts and a manually operated pallet jack (Figures 3, 4, 5, 6 and 7), and two types of powered fork lift trucks (Figures 8 and 9). Table 1 shows the size and weight capacity of the different equipment used in this study and Figures 3–9 show pictures of the MHE and their wheel and casters.

Vibration levels for all MHE were observed for both loaded and empty configurations. The gray plastic and metal carts (Figure 3 and 4) were loaded with the maximum manufacturer recommended capacity of 91 kilograms and the red and green metal carts (Figures 5 and 6) were loaded with the maximum capacity of 182 kilograms. The various carts and MHE were tested both empty and fully loaded at the rated cart or MHE capacity. This produced a range of vibration levels, and as expected, a fully loaded cart or MHE showed lower vibration levels than an empty or partially loaded one. The vibration analysis on these MHE and carts was only done on the vertical orientation, since these levels were the highest.

In order to capture the vibration levels experienced by the MHE on different operating surfaces, the study was conducted both inside and outside a warehouse facility. The internal floor surfaces used for this study comprised of PVC tiled flooring, concrete flooring and ceramic tiled flooring. The external surfaces were asphalt and concrete. The vibration levels were recorded for a distance of approximately 550 meters inside and approximately 1100 meters outside the facility. Vibration levels were also recorded for the fork lift truck and stacker at medium speeds and high (Figure 8 and 9) of 2 and 4 MPH. Table 2 shows the various settings used to capture the vibration levels for the MHE studied.

4.0 RESULTS

The recorded vibration levels were analyzed to determine power den-

Table 2. Experimental Design for Vibration Measurements for MHE.

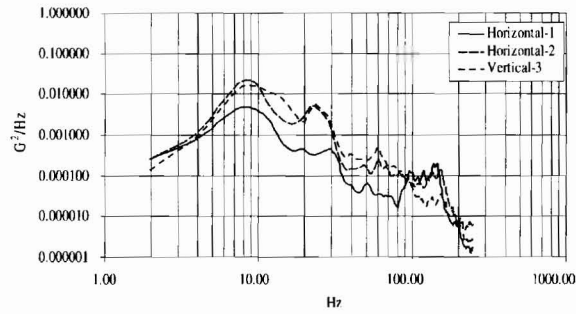
Empty	
Inside Warehouse	Outside Warehouse
Grey plastic cart	Grey plastic cart
Grey metal cart	Grey metal cart
Red metal cart	Red metal cart
Green metal cart	Green metal cart
Pallet jack	Pallet jack
Inside Warehouse	
Stacker and Fork Lift Truck	
Outside Warehouse	
Fork lift: medium speed—2MPH	
Fork lift: high speed—4 MPH	

sity (PD) levels for frequencies ranging between 2–250 Hz. This analysis was performed on data collected from all 3 channels (latitudinal, longitudinal, and vertical). The data obtained from the vertical channel was further analyzed to determine the top 20% power density (PD), lower 80% PD and average PD levels as a function of frequency. For the analyzed data power spectral density (PSD) graphs were plotted for each type of cart and fork lift for respective surfaces. For comparison between the loaded and the empty carts the vibration levels were calculated from the data collected from the vertical channel and were analyzed for the observed the PD for the upper 20% and lower 80% besides the average PD.

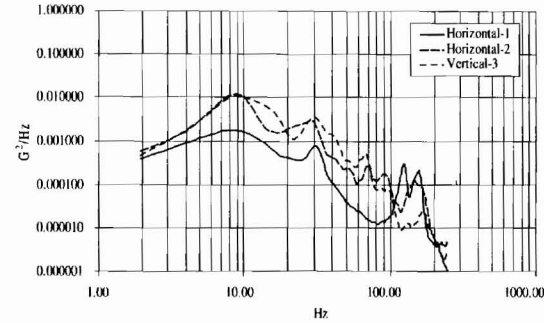
The vibration data was analyzed and the PSD plots are presented below in Figures 10–22.

Table 3. Vibration Analysis.

Vibration Analysis in the Vertical Channel	
Inside Warehouse	Outside Warehouse
Green metal cart: loaded	Green metal cart: loaded
Green metal cart: empty	Green metal cart: empty
Grey plastic cart: loaded	Grey plastic cart: loaded
Grey plastic cart: empty	Grey plastic cart: empty
Grey metal cart: loaded	Grey metal cart: loaded
Grey metal cart: empty	Grey metal cart: empty

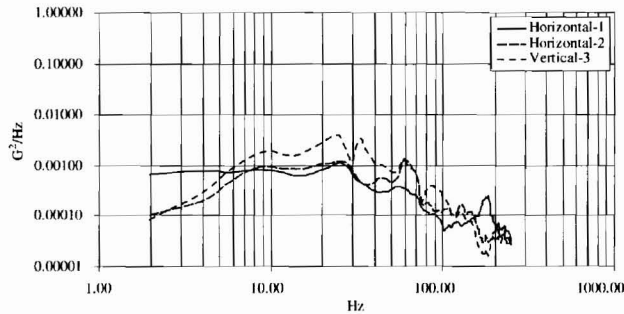


(a)

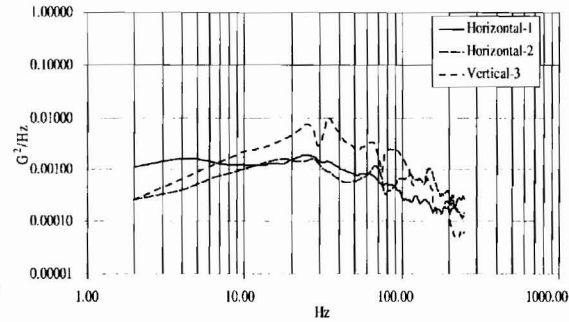


(b)

Figure 10. PSD for Empty Grey Plastic Cart (a) inside and (b) outside the Warehouse.

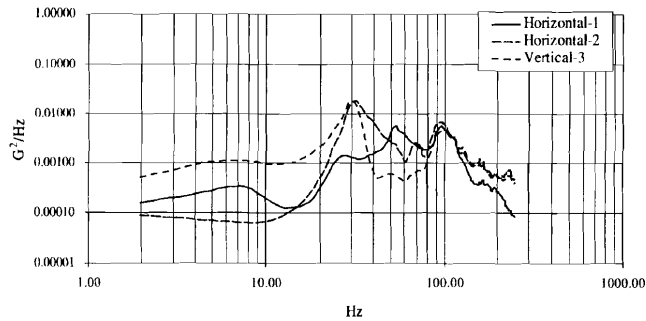


(a)

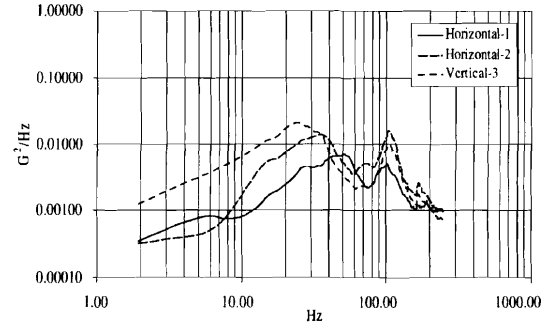


(b)

Figure 11. PSD for Empty Grey Metal Cart (a) inside and (b) outside the Warehouse.

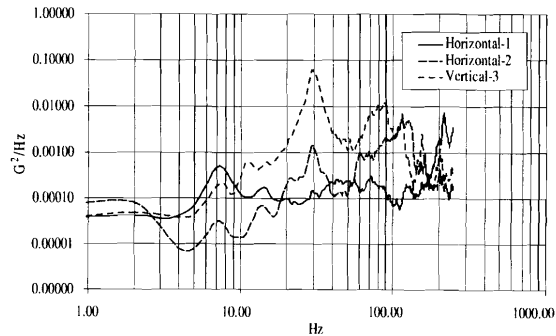


(a)

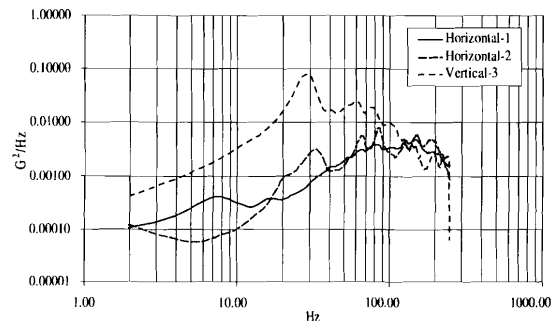


(b)

Figure 12. PSD for Empty Red Metal Cart (a) inside and (b) outside the Warehouse.



(a)



(b)

Figure 13. PSD for Empty Green Metal Cart (a) inside and (b) outside the Warehouse.

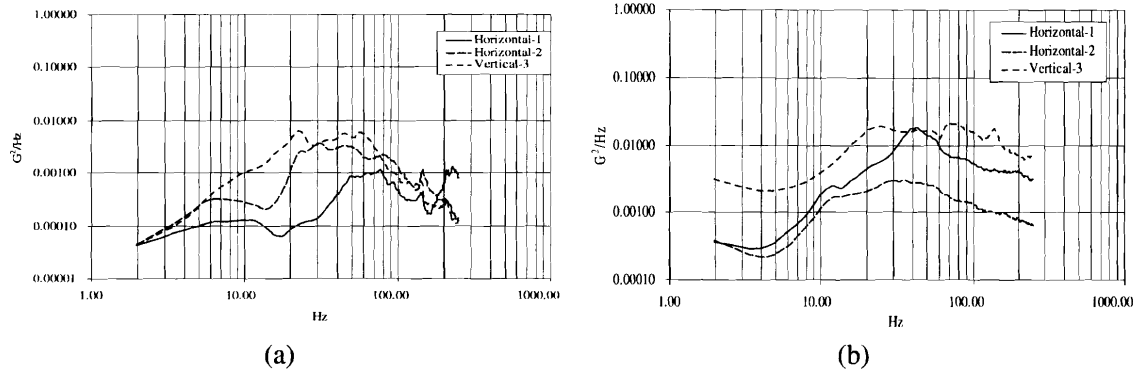


Figure 14. PSD for Empty Pallet Jack (a) inside and (b) outside the Warehouse.

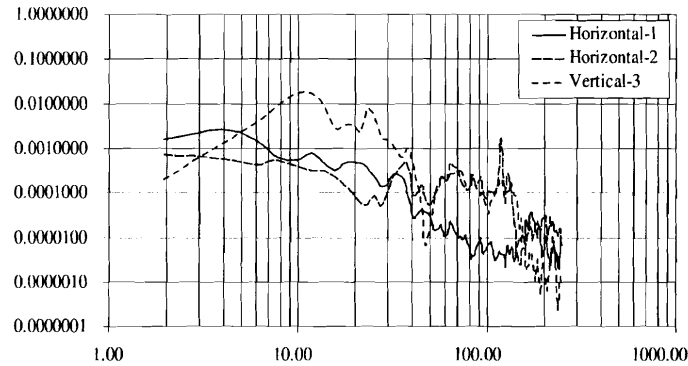


Figure 15. PSD for Empty Stacker inside the Warehouse.

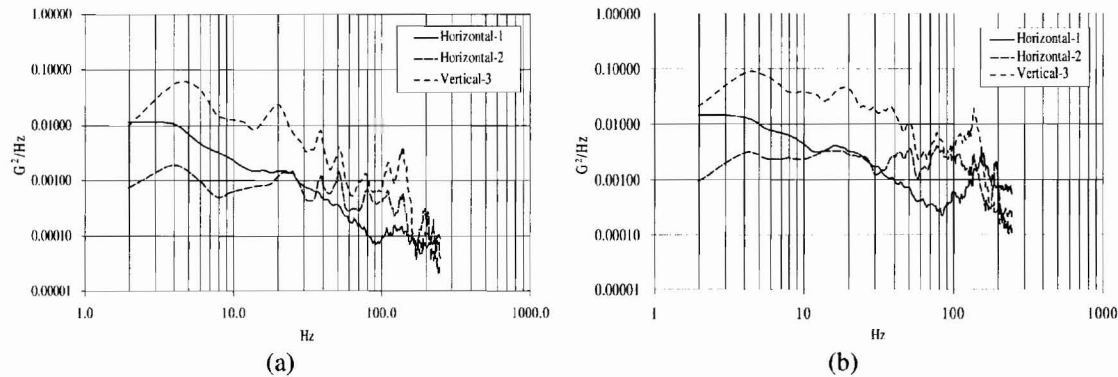


Figure 16. PSD for Empty Stacker outside the Warehouse at (a) Medium and (b) High Speeds.

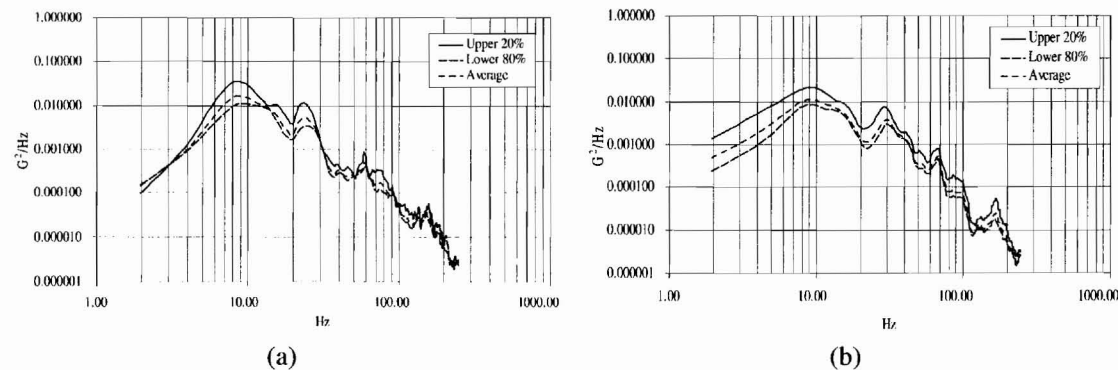


Figure 17. PSD for Vibration Analysis in Vertical Channel for Empty Grey Plastic Carts (a) Inside and (b) Outside the Warehouse.

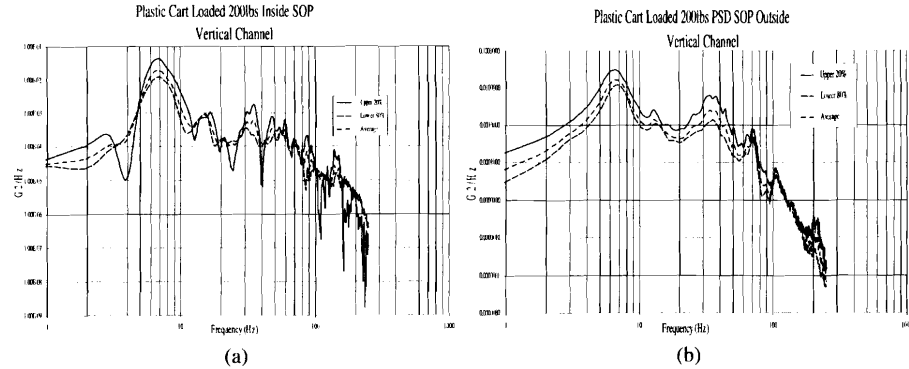


Figure 18. PSD for Vibration Analysis in Vertical Channel for Loaded Grey Plastic Carts (a) Inside and (b) Outside the Warehouse.

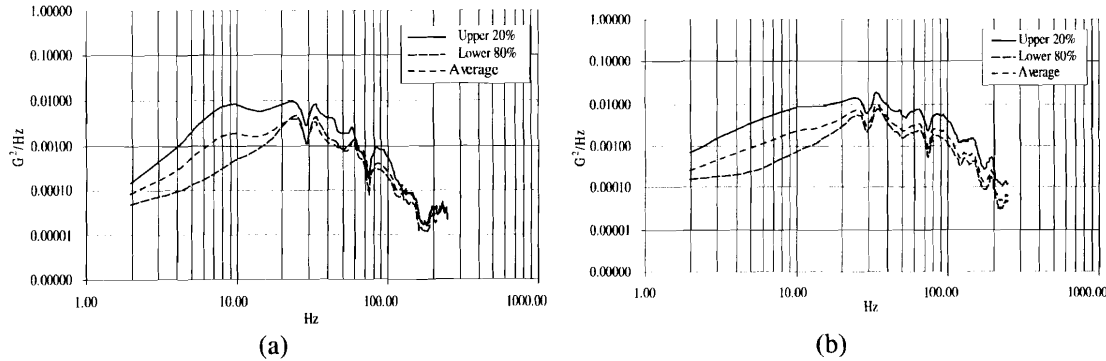


Figure 19. PSD for Vibration Analysis in Vertical Channel for Empty Grey Metal Carts (a) Inside and (b) Outside the Warehouse.

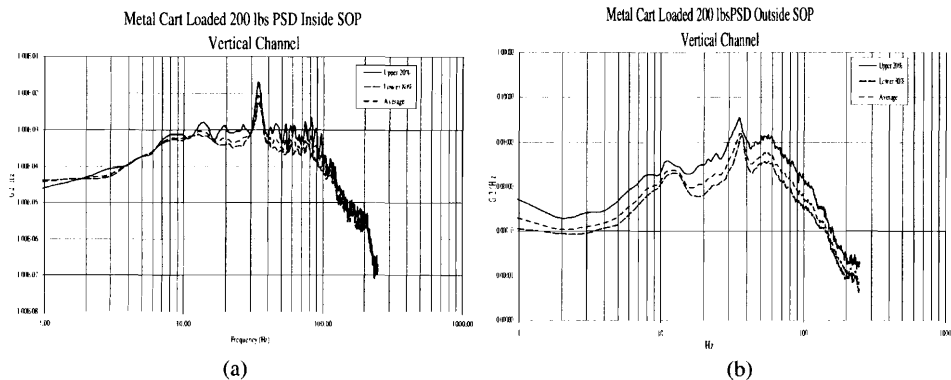


Figure 20. PSD for Vibration Analysis in Vertical Channel for Loaded Grey Metal Carts (a) Inside and (b) Outside the Warehouse.

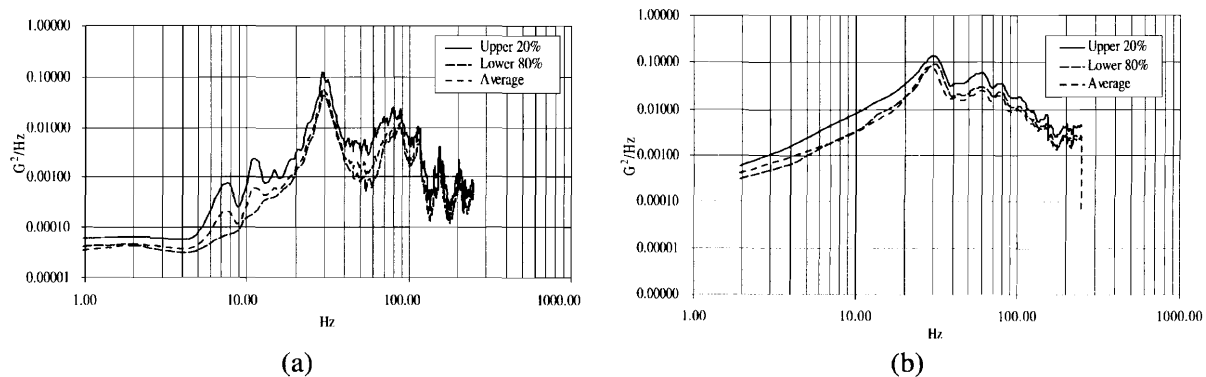


Figure 21. PSD for Vibration Analysis in Vertical Channel for Empty Green Metal Carts (a) Inside and (b) Outside the Warehouse.

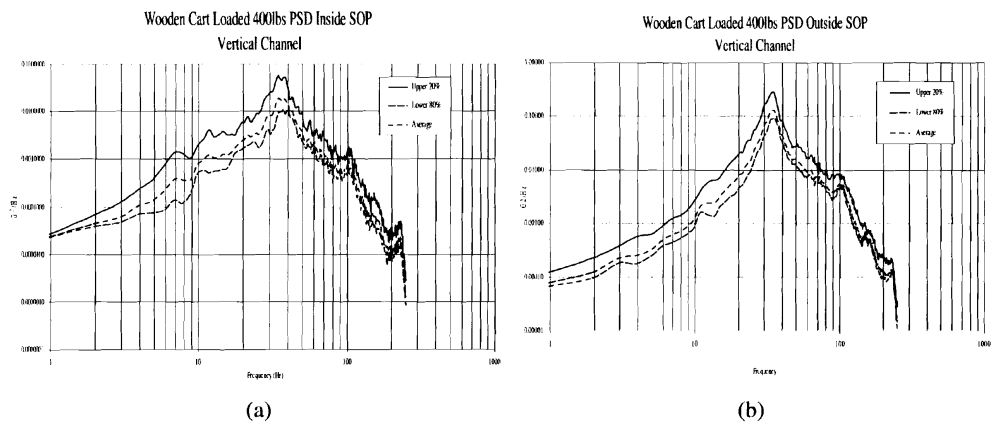


Figure 22. PSD for Vibration Analysis in Vertical Channel for Loaded Green Metal Carts (a) Inside and (b) Outside the Warehouse.

Table 4. *Composite Spectrum for Warehouse and Retail Store Material Handling Equipment.*

Frequency (Hz)	Power Density (G^2/Hz)
2	0.001
5	0.01
15	0.1
25	0.1
30	0.01
100	0.001

4.0 DISCUSSION

Based on reviewing the data from the various Power Density Spectra, it is clear that vibrations levels in the 4–20 Hz range found in these type of product and package conveying equipment are much higher than those found in transport systems such as truck and rail. Also the recent shift by various vibration test method development bodies such as the International Safe Transit Association to lower the vibration intensity levels when simulating for truck transport in this frequency range may not adequately test packages. Previously developed truck composite spectra such as those proposed by ASTM D4169 account for these vibration levels, however it may be important to differentiate transport vibration from material handling vibration as products and packages are exposed much longer in transportation than material handling.

The following composite spectrum has been developed to simulate various forms of manually driven carts and powered material handling carts used in manufacturing and retail.

5.0 CONCLUSIONS

1. The lateral and longitudinal orientations generally show lower vibration levels as compared to vertical. Therefore the vertical vibration levels were measured for empty and loaded MHE.
2. Vibration levels were higher in the outside track as compared to the inside track because of the surface irregularities.
3. Empty carts produced higher vibration levels than the loaded carts.
4. Plastic carts showed lower vibration levels than metal carts.
5. The vibration level and frequencies measured from MHE occur at a higher frequency (8–30Hz) as compared to most transportation vehi-

cle vibrations (2–8Hz). This needs to be included in the ASTM Random Vibration Standards that currently do not test at these levels.

6. A composite spectrum was developed to simulate MHE.

ACKNOWLEDGEMENTS:

The authors would like to thank the Consortium of Distribution Packaging Research, Michigan State University for funding this study. In addition we would like to acknowledge Navnit Narayan and Bob Hurwitz with assisting in obtaining necessary equipment and data collection.

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